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Determining the Temperature Conditions in the Furnace of a Steam Engine

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Abstract—An analytical method is proposed for determining the combustion temperature and gas-flux temperature at any point of a furnace, as well as other characteristics of the furnace process.

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Efficient solid-fuel use in the power industry and in transportation is of great current importance. Railroads operate mainly on electric power and diesel fuel. There is no demand for coal, which is a cheap and readily available fuel, except in power plants generating the power for electric locomotives. The replacement of steam locomotives by electric and diesel locomotives at the end of the 1950s increased freight costs. The costs of railroad transportation are expected to rise further as the prices of power and diesel fuel increase. This will reduce freight and passenger loads and result in growing inefficiency of rail travel. In addition, the combustion products of diesel fuel are pollutants. Toxic materials account for up to 97% of their exhaust gases.

Thanks to new technologies for solid-fuel combustion, steam locomotives may represent an environmentally benign mode of transportation for the twenty-first century [1]. Without considering increase in efficiency and the elimination of deficiencies in locomotive design, we focus in the present work on the key component of the steam engine: the furnace.

On old steam locomotives, the crew expended much effort and time in boiler maintenance. To improve the locomotive, we need automatic control of the thermal processes, so that all the operations associated with heating and steam generation (including monitoring) may be automated. This entails knowledge of the temperatures created in the furnace and the heat transferred by the gases to the boiler pipes and transmitted through the furnace wall to the water, by radiation and convection.

A simple approximate (graph–analytic) method of determining the temperature in a steam-engine furnace was proposed in [2]. This method has a series of deficiencies, since the calculations include a subjective element and, as a rule, the best solution is selected from a range of options. The need to plot graphs for subsequent determination of the furnace temperatures hinders the real-time prediction and automatic control of the furnace process. To eliminate these deficiencies, we have developed a method that may be used in simulating the processes within locomotive and other furnaces.

EQUATIONS FOR THE THERMAL PROCESS AND HEAT TRANSFER IN THE FURNACE

The thermal conditions in the furnace are characterized by a series of dependences (a family of curves; Fig. 1). Straight line *cd* corresponds to the theoretical combustion temperature t_0 obtained from the thermal equation with complete fuel combustion. Curve t_{1x} (curve *ae*), characterizing the variation in the effective temperature t_1, shows the rate of combustion of the volatiles released from the fuel. Curve *af* corresponds to the temperature t^* due to radiant heat transfer. Curve t_{2x} (curve *ag*) is the variation in the effective temperature t_2 in the furnace.

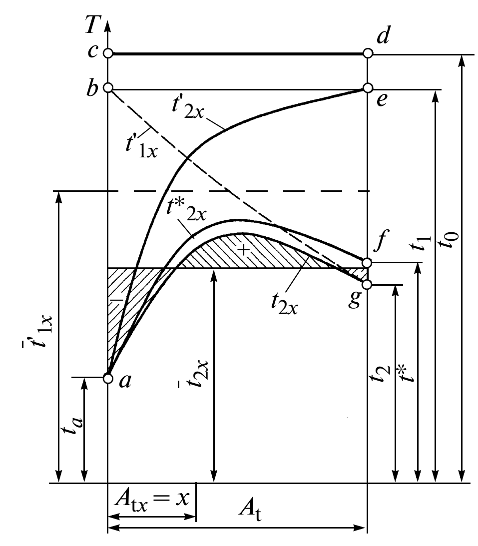

Fig. 1. Operational temperature curves of furnace.

The difference in height between line *cd* and curve *ae* corresponds to the temperature drop due to losses on combustion; the difference in height of the curves *ae* and *af* corresponds to the temperature drop due to radiant heat transfer; and the difference in height of the curves *af* and *ag* corresponds to the temperature drop due to convective heat transfer.

The thermal and heat-transfer equations used to investigate the temperature in a steam-engine furnace were given in [2]. The thermal equation expresses the relation between the gas-flux temperature in the cross section of the gas line and the heat Q passing through that cross section

$$Q = Mt + Nt^2. \quad (1)$$

Here $M = \mu B_h G_h c$, $N = \mu B_h G_h \delta$ are coefficients, while

$$G_h c = 0.55\frac{\mathrm{C}}{\mathrm{CO_2 + CO}} + 2.1\times10^{-3}\mathrm{C} + 4.06\times10^{-2}\mathrm{H} + 4.5\times10^{-3}\mathrm{W};$$

$$G_h \delta = 4.45\times10^{-5}\frac{\mathrm{C}}{\mathrm{CO_2 + CO}} + 1.3\times10^{-6}\mathrm{C} + 4.4\times10^{-6}\mathrm{H} + 5\times10^{-7}\mathrm{W}$$

C, H, W are the contents of carbon, hydrogen, and water, respectively, in the fuel; CO and CO_2 are the carbon-monoxide and carbon-dioxide contents, respectively, in the combustion products; μ is the mechanical completeness of fuel combustion; B_h is the quantity of fuel consumed per hour.

The heat-transfer equation expresses the relation between the gas-flux temperature in the cross section of the gas line and the heat obtained by the surface exposed to the gases up to this cross section

$$(M + 2Nt_{\mathrm{w}})\ln\frac{t_{\mathrm{in}} - t_{\mathrm{w}}}{t_{\mathrm{fi}} - t_{\mathrm{w}}} + 2N(t_{\mathrm{in}} - t_{\mathrm{fi}}) = kA, \quad (2)$$

where t_{in}, t_{fi} are the gas temperatures at the beginning and end of the section; t_{w} is the water temperature in the boiler; k is the heat-transfer coefficient of the heated surface; A is the surface area exposed to the gas.

If we know the initial and final gas temperatures and the heated surface area, we may determine the heat-transfer coefficient from Eq. (2) and hence determine the gas temperature in any intermediate cross section.

Suppose that we know the rank of coal; the composition of the combustion products; and the furnace characteristics. We want to find, at any point of the boiler, the combustion temperature t_{1x}, the effective gas temperature t_{2x}, the chemical incompleteness of fuel combustion Q_{2x}, and the heat transmitted by the gases in convective and radiant heat transfer.

For the steam-engine furnace, we may write the heat-transfer equation in the form

$$(M + 2Nt_{\mathrm{w}})\ln\frac{t_1 - t_{\mathrm{w}}}{(t_1')_x - t_{\mathrm{w}}} + 2N(t_1 - (t_1')_x) = k_{\mathrm{f}}(A_{\mathrm{f}})_x, \quad (3)$$

where t_{1x}' is the effective temperature in cross section x of the furnace; k_{f} is the heat-transfer coefficient of the furnace walls; $A_{\mathrm{f}x} = x$ is the surface area of the furnace up to cross section x.

Curve *bg* in Fig. 1 corresponds to Eq. (3). Initially ($A_{\mathrm{f}x} = 0$), the temperature could only be t_1 if there were no chemical losses due to the combustion of volatiles released from the fuel. Obviously, these losses are very large initially. (They are determined by the heat content of the volatiles.)

The heat acquired by the gases through the furnace surface is

$$\begin{aligned} Q_{\mathrm{f}} &= (Mt_1 + Nt_1^2) - (Mt_2 + Nt_2^2) \\ &= M(t_1 - t_2) + N(t_1^2 - t_2^2). \end{aligned} \quad (4)$$

We may express Q_{f} in terms of the mean gas temperature $(\dot{t}_1')_x$

$$Q_{\mathrm{f}} = k_{\mathrm{f}}A_{\mathrm{f}}(\dot{t}_{1x}' - t_{\mathrm{w}}), \quad (5)$$

where A_{f} is the furnace's surface area.

Equating the right sides of Eqs. (4) and (5), we obtain the mean effective gas temperature

$$\dot{t}_{1x}' = t_{\mathrm{w}} + \frac{M(t_1 - t_2) + N(t_1^2 - t_2^2)}{k_{\mathrm{f}}A_{\mathrm{f}}}. \quad (6)$$

On the basis of Eq. (3) and the fact that $t_{1x} = t_2$ at the end of the furnace surface (Fig. 1), we may write Eq. (6) in the form

$$\dot{t}_{1x}' = t_{\mathrm{w}} + \frac{M(t_1 - t_2) + N(t_1^2 - t_2^2)}{(M + 2Nt_{\mathrm{w}})\ln\dfrac{t_1 - t_{\mathrm{w}}}{t_2 - t_{\mathrm{w}}} + 2N(t_1 - t_2)}. \quad (7)$$

If we use a simpler temperature dependence of the gases' specific heat and set $N = 0$ in Eq. (7), we obtain

$$\dot{t}_{1x}' = t_{\mathrm{w}} + \frac{t_1 - t_2}{\ln\dfrac{t_1 - t_{\mathrm{w}}}{t_2 - t_{\mathrm{w}}}}. \quad (8)$$

The heat extracted through the hot furnace surface is

$$Q_{\mathrm{f}} = (Q_0 - Q_2' - Q_2'') - (Mt_2 + Nt_2^2), \quad (9)$$

where Q_0 is the heat available; Q_2' is the heat loss due to the chemical incompleteness of fuel combustion; Q_2'' is the heat loss due to the mechanical incompleteness of fuel combustion; t_2 is the gas temperature at the furnace output (at input to the boiler's tubular section).

Given that this heat is transmitted by convective and radiant heat transfer, we write

$$Q_{\mathrm{f}} = k_{\mathrm{f}}A_{\mathrm{f}}(\dot{t}_{2x} - t_{\mathrm{w}}) + \sigma_0 A_{\mathrm{r}}\left[\left(\frac{\dot{t}_{2x} + 273}{100}\right)^4 - \left(\frac{t_{\mathrm{w}} + 273}{100}\right)^4\right]. \quad (10)$$

Equating the right sides of Eqs. (9) and (10) and neglecting the last term in square brackets (because it is small), we obtain

$$(Q_0 - Q_2' - Q_2'') - (Mt_2 + Nt_2^2) = k_{\mathrm{f}}A_{\mathrm{f}}(\dot{t}_{2x} - t_{\mathrm{w}}) + \sigma A_{\mathrm{r}}\left(\frac{(\dot{t}_2)_x + 273}{100}\right)^4, \quad (11)$$

where σ is the Stefan–Boltzmann constant; A_{r} is the radiant surface area.

From Eq. (11), by trial and error, we find $(\dot{t}_2)_x$.

According to Eq. (1)

$$Q_0 - (Q_2' + Q_2'') = Mt_1 + Nt_1^2. \quad (12)$$

From Eq. (12)

$$t_1 = \frac{\sqrt{M^2 + 4N(Q_0 - Q_2' - Q_2'')} - M}{2N}. \quad (13)$$

We assume that $A_{\mathrm{f}} = 1$ and $t_1 = 1$. Then the area under line *be* in Fig. 1 will also be one. If the initial temperature (when $A_{\mathrm{f}x} = 0$) could reach t_1, the heat liberated (the area under line *be*) would be consumed so that the mean gas temperature was $\dot{t}_{1x}'$. According to Eq. (3), the variation of temperature $\dot{t}_{1x}'$ would then be determined by the curve *bg*. However, because of heat losses, the temperature t_1 increases in accordance with curve *ae* and, as a result of the heat liberated (the area under curve *ae*), the effective temperature will correspond to curve *ag*, while the mean gas temperature will be $\dot{t}_{2x}$. Therefore, we assume that the ratio of the area under curve *ae* to the area under line *be* will correspond to the ratio of the temperatures $\dot{t}_{2x}$ and $\dot{t}_{1x}'$, or the ratio of $\dot{t}_{2x}$ and $\dot{t}_{1x}'$, will be equal to the area S under curve *ae*

$$\frac{\dot{t}_{2x}}{\dot{t}_{1x}'} = S, \quad (14)$$

In the gas flux above the fuel (coal) surface, there is a sharp temperature gradient associated with thermal acceleration of combustion. The combustion rate of the volatiles depends on their rate of liberation from the solid fuel and the concentration of the reagents. The liberation of volatiles is described by a first-order rate equation, as shown in [3]. Therefore, the mathematical description of curve *ae* may be based on a piecewise-linear function

$$y = a + \frac{b + x}{c + x}. \quad (15)$$

By integrating Eq. (15), we obtain an expression for the area S_x under curve *ae* in the general case, on the section from $x = x_{\mathrm{in}}$ to $x = x_{\mathrm{fi}}$

$$S_x = \int_{x_{\mathrm{in}}}^{x_{\mathrm{fi}}}\left(a + \frac{b + x}{c + x}\right)\mathrm{d}x = a(x_{\mathrm{fi}} - x_{\mathrm{in}}) + x_{\mathrm{fi}} - x_{\mathrm{in}} + (b - c)\ln\left|\frac{c + x_{\mathrm{fi}}}{c + x_{\mathrm{in}}}\right|. \quad (16)$$

When $x_{\mathrm{in}} = 0$ and $x_{\mathrm{fi}} = 1$, we obtain the area under curve *ae*

$$S = a + 1 + (b - c)\ln\left|\frac{c + 1}{c}\right|. \quad (17)$$

When $x = 0$, the furnace temperature is t_a, and we may write $g = \frac{t_a}{t_1} = y$.

When $x = 1$, the furnace temperature is t_1, and $y = 1$. On that basis, in view of Eqs. (15) and (17), we may write a system of three equations with the unknowns a, b, and c

$$\left.\begin{aligned} g &= a + \frac{b}{c}; \\ 1 &= a + \frac{b + 1}{c + 1}; \\ S &= a + 1 + (b - c)\ln\left|\frac{c + 1}{c}\right|. \end{aligned}\right\} \quad (18)$$

Solution of Eq. (18) yields the transcendental equation

$$S = 1 + (1 - g)c + c(1 + c)(g - 1)\ln\left|\frac{c + 1}{c}\right|. \quad (19)$$

From equation (19), by trial and error, we find c and hence the coefficients $a = (1 - g)c$ and $b = (g - a)c$.

Substituting these values into Eq. (15), we find the temperature t_{1x} at any point of the furnace space. The formula $t_{1x} = f(x)$ characterizes the rate of combustion of the volatiles released from the fuel. From this formula, we calculate the losses Q_{2x}' due to the chemical incompleteness of fuel combustion at a specific point of the furnace. From Eq. (1)

$$Q_{2x}' = Q_0 - Q_2'' - \lfloor Mt_{1x} - Nt_{1x}^2 \rfloor. \quad (20)$$

In other words, the relative loss of heat as a result of fuel combustion (%) is

$$q_{2x}' = \frac{Q_0 - Q_2'' - Mt_{1x} - Nt_{1x}^2}{Q_0} \times 100. \quad (21)$$

We now consider the effective-temperature variation in the furnace space, which will be considerably less than t_{1x} on account of convective and radiant heat transfer. The temperature t_2 at point g on curve ag (Fig. 1) is found experimentally by measuring the gas temperature. We proceed as follows to find the vertical coordinate of curve ag at other points.

For an infinitesimal section Δx, the temperature t_{2x} will be approximately equal to the mean gas temperature $\bar{t}_{2\Delta x}$ in this section. We again consider the temperatures with respect to (t_1') and $(t_1')_{\Delta x}$. Then, taking account of Eq. (14), we may write

$$\frac{t_{2x}}{t'_{1x}} = \frac{(t_1)_x}{t_1} = \frac{(t_1)_x}{1}. \tag{22}$$

Replacing the small-curvature curve bg in Fig. 1 by a straight line, we obtain

$$t'_{1x} = 1 - x(1 - t_2). \tag{23}$$

We see that Eq. (23) is considerably simpler than Eq. (3). Now Eq. (22) takes the form

$$\frac{t_{2x}}{1 - x(1 - t_2)} = a + \frac{b + x}{c + x}, \tag{24}$$

From Eq. (24), we obtain

$$t_{2x} = [1 - x(1 - t_2)]\left(a + \frac{b + x}{c + x}\right). \tag{25}$$

Thus, without subjective estimates and graph plotting, we have found the characteristics of the furnace process—the combustion temperature t_{1x}; the effective gas temperature t_{2x}; and the chemical incompleteness of fuel combustion Q'_{2x}—at any point of the furnace. This is sufficient for regulation of the furnace process.

HEAT DISTRIBUTION IN FURNACE

For most fuels, the temperature t_a fluctuates in the range 550–900°C and is assumed to be 600–700°C in plotting the graphs (since its precise determination is difficult), as noted in [2]. This approximation has little influence on the precision of the results. Such fluctuation in t_a is relatively unimportant when determining the furnace temperature, but results in significant error when finding the quantity of heat distributed in the furnace. The error may only be reduced by more precise calculation of t_a.

We integrate Eq. (25)

$$\begin{aligned}\int[1 - x(1 - t_2)]\left(a + \frac{b + x}{c + x}\right)\mathrm{d}x &= (a + 1)x + (b - c)\\ &\times[1 - c(t_2 - 1)]\ln|c + x| + (t_2 - 1)(c + x)\\ &\times\left[b + \frac{(c + x)}{2} - 2c + \frac{ax^2}{2(c + x)}\right].\end{aligned} \tag{26}$$

If we denote by x_{in} and x_{fi}, respectively, the beginning and end of the range of interaction, while S_{2x} is the area under curve t_{2x} within this section, we may write Eq. (26) in the form

$$\begin{aligned}(S_2)_x &= \int_{x_{\text{in}}}^{x_{\text{fi}}}[1 - x(1 - t_2)]\left(a + \frac{b + x}{c + x}\right)\mathrm{d}x = (a + 1)\\ &\times(x_{\text{fi}} - x_{\text{in}}) + (b - c)[1 - c(t_2 - 1)]\ln\left|\frac{c + x_{\text{fi}}}{c + x_{\text{in}}}\right|\\ &+ (t_2 - 1)\Big[(x_{\text{fi}} - x_{\text{in}})(b - 2c)\\ &+ \frac{(c + x_{\text{fi}})^2 - (c + x_{\text{in}})^2}{2} + \frac{a}{2}(x_{\text{fi}}^2 - x_{\text{in}}^2)\Big].\end{aligned} \tag{27}$$

If we express a and b in terms of g from Eq. (18), substitute the result into Eq. (27), and set $x_{\text{in}} = 0$ and $x_{\text{fi}} = 1$, we obtain the area S_{ag} under curve ag

$$\begin{aligned}S_{ag} &= (1 - g)c + 1 + c[g(1 + c) - c - 1]\\ &\times[1 - c(t_2 - 1)]\ln\left|\frac{c + 1}{c}\right| + (t_2 - 1)\\ &\times\left\{c[g(1 + c) - c - 1] + \frac{(1 - g)c + 1}{2}\right\}.\end{aligned} \tag{28}$$

From the first relation in Eq. (18), we find that

$$g = 1 + \frac{S - 1}{(1 + c)c\ln\left|\frac{c + 1}{c}\right| - c}. \tag{29}$$

Substituting this expression into Eq. (28), we find S_{ag} as a function of the single variable c

$$\begin{aligned}S_{ag} &= 1 - \frac{(S - 1)c}{(1 + c)c\ln\left|\frac{c + 1}{c}\right| - c}\\ &+ c\left[\left(1 + \frac{S - 1}{(1 + c)c\ln\left|\frac{c + 1}{c}\right| - c}\right)(1 + c) - c - 1\right]\\ &\times[1 - c(t_2 - 1)]\ln\left|\frac{c + 1}{c}\right| + (t_2 - 1)\\ &\times\left\{c\left[\left(1 + \frac{S - 1}{(1 + c)c\ln\left|\frac{c + 1}{c}\right| - c}\right)(1 + c) - c - 1\right]\right.\\ &\left.+ 0.5 - \frac{(S - 1)c}{2\left[(1 + c)c\ln\left|\frac{c + 1}{c}\right| - c\right]}\right\}.\end{aligned} \tag{30}$$

The heat transferred through the hot furnace surface is given by Eq. (9), while the heat entrained by the gases to the boiler's tubular section is $Mt_2 + Nt_2^2$. We express the ratio of these quantities by m

$$m = \frac{Q_0 - Q_2' - Q_2''}{Mt_2 - Nt_2^2} - 1 \tag{31}$$

or else in terms of the area

$$m = \frac{S - S_{ag}}{S_{ag} - g}. \tag{32}$$

Now we may add Eq. (32) to Eq. (18). Solution of this system for c permits the determination of a, b, and g, as well as t_a, which is accurately determined in this case.

On the basis of Eqs. (4) and (5)

$$Mt^* + N(t^*)^2 = Mt_2 + Nt_2^2 + k_f^c A_f(\dot{t}_{2x} - t_w). \tag{33}$$

From Eq. (33)

$$t^* = \frac{\sqrt{M^2 + 4N(Mt_2 + Nt_2^2 + k_f^c A_t((\dot{t}_2)_x - t_w))} - M}{2N}. \tag{34}$$

The heat transferred by the gases to individual section of the furnace by convective and radiant means will be proportional to the mean gas temperature. For an infinitesimal section, this temperature is close to the effective temperature t_{2x}. The temperature drop due to conduction in cross section x is equal to the sum of the temperature drops in the preceding sections. In other words, it is proportional to the area under curve ag. Knowing the total temperature drop for the whole furnace (the difference between t^* and t_2), we may write

$$t_x^* = t_{2x} + \frac{S_{2x}}{S_{ag}}(t^* - t_2), \tag{35}$$

where t_x^* is the temperature in section x as a result of radiant heat transfer.

Substituting Eq. (25) into Eq. (35) and setting $x_{in} = 0$ and $x_{fi} = x$ in Eq. (27), we obtain

$$t_x^* = [1 - x(1 - t_2)]\left(a + \frac{b + x}{c + x}\right) + \frac{t^* - t_2}{S_{ag}} \times \left\{(b - c)\ln\left|\frac{c + x}{c}\right| + (a + 1)x + (t_2 - 1) \times \left[bx - (b - c)c\ln\left|\frac{c + x}{c}\right| + \frac{x^2(a + 1) - 2cx}{2}\right]\right\}. \tag{36}$$

The t_x^* curve (af in Fig. 1) bounds the region of convective and radiant heat transfer. The area between curves ae and af corresponds to the radiant heat transfer to the gases; the area between curves af and ag corresponds to the convective heat transfer to the gases.

To calculate the convective heat transfer, we need to find the area S_x^{co} between curves af and ag. The area under curve af is determined by integrating Eq. (36). Obviously, the integral of the first term on the right side determines the area S_{2x}, while the integral of the second term determines S_x^{co}. Then, integrating the second term in Eq. (36), we obtain

$$\begin{aligned}&\left\{(b - c)[c(t_2 - 1) + 1]c\ln\left(\frac{c + x_{fi}}{c + x_{in}}\right) + (b - c)\right.\\ &\times[1 - c(t_2 - 1)]S_x^{co} = \frac{t^* - t_2}{S_{ag}}[x_{fi}\ln(c + x_{fi})\\ &- x_{in}\ln(c + x_{in}) - (x_{fi} - x_{in})(1 + \ln c)] + \frac{t_2 - 1}{6}\\ &\left.\times(x_{fi}^3 - x_{in}^3)(1 - a) + \frac{x_{fi}^2 - x_{in}^2}{2}[a + 1 + (t_2 - 1)(b - c)]\right\}\end{aligned} \tag{37}$$

The area S_x^r between curves ae and af corresponds to the radiant heat transfer in the given section of the furnace

$$S_x^r = S_x - S_x^{co} - S_{2x}. \tag{38}$$

Thus, on the basis of Eqs. (16), (37), and (38), we may calculate the heat transferred by convective and radiant means, as well as the thermal content of the gases at any point of the furnace.

More complete fuel combustion requires the liberation and combustion of the volatiles before the gases enter the boiler's tubular section. In that case, the increase in temperature t_{1x} in the furnace will end. To investigate the combustion of volatiles, which depends on the ratio of the furnace volume to the quantity of fuel that must be burnt, we find the derivative of the function in Eq. (15)

$$\left(a + \frac{b + x}{c + x}\right)' = \frac{c - b}{(c + x)^2} \tag{39}$$

and calculate its value when $x = 1$. A value less than 0.105 indicates that the tangent to this curve is small. In other words, the reaction of the volatiles is largely complete, and there is practically no further rise in combustion temperature. If this is observed when x is considerably less than one, we conclude that the furnace volume is larger than is needed for the combustion of the given quantity of fuel. Consequently, the combustion temperature may fall, and the inverse

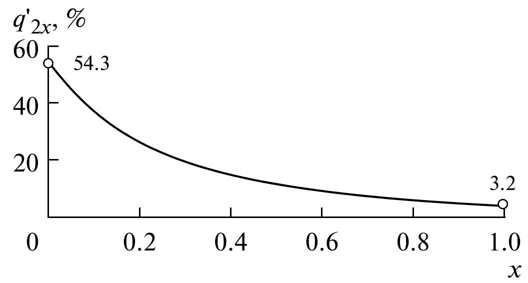

Fig. 2. Losses due to the chemical incompleteness of fuel combustion.

reaction may begin, with associated increase in CO content in the gas. A large tangent at $x = 1$ shows that the temperature is still rising, combustion is not complete, and a larger furnace is required for complete combustion.

Thus, from Eq. (39), it is simple to determine the combustion temperature and the optimal furnace size for several points of the furnace space.

To find points where the maximum temperature is reached, we take the derivative of Eq. (25)

$$t_{2x} = \frac{c-b}{(c+x)^2} + (t_2 - 1)\left[\frac{x^2 + c(b+2x)}{(c+x)^2} + a\right]. \quad (40)$$

Equating this derivative to zero, we obtain

$$x = \sqrt{c^2 - \frac{c(ac+b)}{a+1} - \frac{c-b}{(t_2-1)(a+1)}} - c. \quad (41)$$

Substituting this result for x into Eq. (25), we determine the maximum temperature $t_{2x\max}$ of the furnace gases.

EXAMPLE

On the basis of the proposed method, we now investigate the temperature within an FD locomotive furnace, when using G coal (72% C, 4.9% H, 6.4% O, 1.3% N, 3% S, and 4.8% water; heat of combustion 28780 kJ kg). Overdriven conditions are employed (313 kg/m^2 h; $B_h = 2203$ kg/h). The combustion products are 13.7% CO_2 and 0.9% Co; $k_f = 35.2$ kJ/h m^2 °C; $\mu = 0.885$; $t_w = 200$°C; $t_2 = 1200$°C; $A_f = 31.2$ m^2; $A_r = 16.15$ m^2.

From Eq. (1), we determine M and N

$$G_b c = 12.92;$$

$$M = 0.885 \times 2203 \times 12.92 = 25190 \text{ kJ/h °C};$$

$$G_h b = 1.412 \times 10^{-3}; \quad N = 0.885 \times 2203 \times 1.412 \times 10^{-3} = 2.7529 \text{ kJ/h °C}^2.$$

Then we find

$$Q_0 = 28780 \times 2203 = 63402340 \text{ kJ/h}.$$

$$Q_2' = 4.19\left(56.9 \times 72 \times \frac{0.9}{13.7 + 0.9} \times 0.885 \times 2203\right) = 2063000 \text{ kJ/h}.$$

$$Q_2'' = (1 - 0.885) \times 2203 \times 28780 = 7291270 \text{ kJ/h}$$

From Eq. (13), $t_1 = 1794$°C.

According to Eq. (11), $\dot{t}_{2x} = 1271$°C.

From Eq. (34), $t^* = 1233$°C.

From Eq. (8), we find the mean effective gas temperature $t'_{1x} = 1474$°C.

Now we have all the data we need to find the furnace characteristics $t_1 = 1794$°C, $t_2 = 1200$°C, $\dot{t}_{2x} = 1271$°C, $t^* = 1233$°C, $\dot{t}'_{1x} = 1474$°C.

From Eq. (14), $S = 0.8623$.

From Eq. (31), $m = 0.5807$. Substituting this value into Eq. (32), we obtain a solution by trial and error, taking account of Eq. (30). We find that $c = 0.2351$. Then, from Eq. (29), $g = 0.4416$ and $t_a = 792$°C. Hence, from Eq. (18) $a = (1 - 0.4416) \times 0.2351 = 0.1313$ and $b = (0.4416 - 0.131) \times 0.2351 = 0.073$.

Substituting the results into Eq. (15), we obtain the variation in combustion temperature in the furnace $y = 0.1313 + \dfrac{0.073 + x}{0.2351 + x}$.

From Eqs. (20) and (21), we find the losses due to the chemical incompleteness of fuel combustion at the required point of the furnace. If we replace t_{1x} in Eqs. (20) and (21) by the expression for y, we obtain the losses as a function of the change in furnace area (Fig. 2).

Then, from Eq. (25), we find the effective temperature in the furnace space $t_{2x} = [1 - x(1 - 0.6689)]\left(0.1313 + \dfrac{0.073 + x}{0.2351 + x}\right)$.

From Eq. (36), we find the position of the t_x^* curve.

From Eq. (41), we determine the value of x at which the effective gas temperature reaches its maximum value in the furnace: $x = 0.448$.

Substituting this value into Eq. (25), we obtain

$$t_{2\max} = [1 - 0.448(1 - 0.6689)] \times \left(0.1313 + \frac{0.073 + 0.448}{0.2351 + 0.448}\right) = 0.7614 \text{ or } 1366\text{°C}.$$

The temperature variation in the furnace is shown in Fig. 3.

We now consider the match between the furnace volume and the quantity of fuel. From Eq. (39), when $x = 0.95$ and $x = 1$, we obtain

$$x = \frac{0.2351 - 0.073}{(0.2351 + 0.95)^2} = 0.115;$$

$$x_1 = \frac{0.2351 + 0.073}{(0.2351 + 1)^2} = 0.106.$$

This indicates that the increase in combustion temperature has practically stopped at the end of the furnace. The furnace volume permits coal combustion at a rate of 2203 kg/h. However, with in very overdriven conditions, the furnace volume must evidently be increased to ensure more complete combustion.

We now determine the radiant and convective heat transfer and the heat entrained by the gases to the boiler's tubular section.

From Eqs. (37), (38), and (27), about two fifths of the heat transfer (1422505 kJ) is convective in the section from $x_{\text{in}} = 0.4$ to $x_{\text{fi}} = 0.5$, while three fifths (3411014 kJ) is entrained by the furnace gases.

When $x_{\text{in}} = 0$ and $x_{\text{fi}} = 1$, the ratio of the areas corresponding to radiant and convective heat transfer and the gases' heat content is different: 0.3445, 0.0229, and 0.6326, respectively. These values are equivalent to 18619560, 1237701, and 34190809 kJ. Hence, 6.6% of the heat transfer is convective, while 93.4% is radiant. In all, 36.7% of the heat (about a third) is consumed in the furnace, while the remaining 63.3% (about two thirds) is entrained by the gases to the boiler's tubular section.

On the basis of Eqs. (15), (25), and (36), we may calculate the combustion temperature t_{1x}, the effective gas temperature $t_{2\mathbf{x}}$ in the furnace volume, and the temperature t_x^* due to radiation at any point of the furnace volume. From Eqs. (20) and (21), we calculate the losses Q'_{2x} and q'_{2x} due to the chemical incompleteness of fuel combustion. From Eqs. (37) and (38), the heat transferred to the water in the boiler by convective and radiant means may be determined at any point of the furnace. From Eq. (27), we may calculate the heat content of the gases S_{2x}. By means of Eqs. (39) and (41), we may establish whether the furnace volume is matched to the quantity of fuel that must be burnt and find the cross section of the furnace volume corresponding to maximum temperature $t_{2x\max}$. Analytical determination of these characteristics is important not only for automation of the furnace process but also for analysis of the temperature deformation at the furnace walls. The proposed method is well suited to computer calculations.

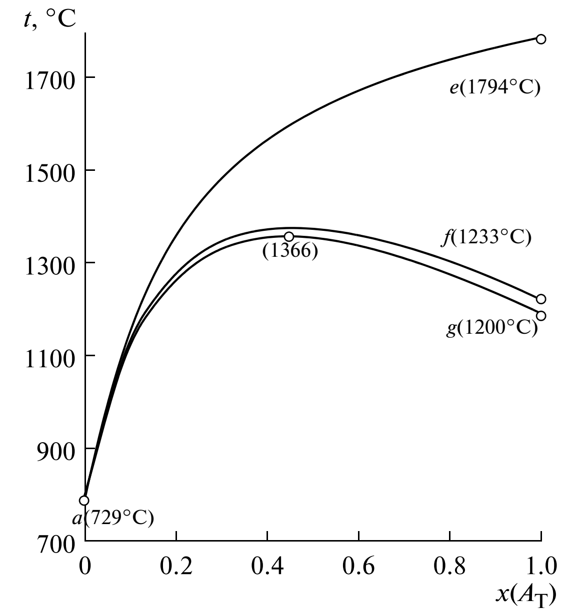

Fig. 3. Family of temperature curves for the furnace space.

REFERENCES

1. Olenev, E.A., Nontraditional Use of Solid Fuel in Rail Transportation, *Naukoemkie Tekhnol.*, 2007, no. 1, pp. 61–66.
2. Syromyatnikov, S.P., Thermal Operation of Boilers and the Dynamics and Steam Distribution in a Locomotive, *Trudy Moskovskogo elektromekhanicheskogo institut inzhenerov transporta* (Proceedings of Moscow Electromechanical Institute of Transportation Engineers), Moscow: Gosudarstvennoe Transportnoe Zheleznodorozhnoe Izd., 1940, pp. 5–57.
3. Strunnikov, M.F., Emission Rate of Volatiles from Solid Fuel, *Issledovanie protsessov goreniya natural'nogo topliva* (Combustion of Natural Fuel), Moscow: Gosudarstvennoe Energeticheskoe Izd., 1948, pp. 110–116.